Office of Naval Research
Department of the Navy

Contract N00014-67-0094-0009

ULTRASONIC CAVITATION IN LIQUID HELIUM

by

Din-Yu Hsieh

Division of Engineering and Applied Science
CALIFORNIA INSTITUTE OF TECHNOLOGY
Pasadena, California

Div. of Engrg. + Appl. Scies.

Report No. 85-44

March 1968

Office of Naval Research
Department of the Navy
Contract N00014-67-0094-0009

ULTRASONIC CAVITATION IN LIQUID HELIUM

by

Din-Yu Hsieh

Division of Engineering and Applied Science
California Institute of Technology
Pasadena, California

Report No. 85-44 March 1968

Abstract

Based on the new interpretation that rotons behave like tiny quantized vortex rings, a theory is constructed to give a complete picture of ultrasonic cavitation in liquid helium. The problem of nuclei of cavitation is approached from a new direction. Questions like the λ-peak of the audible threshold, the distinction among audible, incipient visible and desinent visible cavitation thresholds in He II, the lack of such distinction in He I, the reduction of audible threshold by rotation in He II and the absence of such reduction in He I, are satisfactorily explained. The relevance of the present theory to cavitation in ordinary liquids is briefly discussed.

I. Introduction

The existing experimental information about ultrasonic cavitation in liquid helium consists of the following main features:

(i) The audible cavitation threshold maintains a fairly constant level between 1000 - 2000 dynes/cm^2 for both He II and He I for $T > 1.2°K$, except in the neighborhood of T_λ, where the threshold rises to as high as 6,000 dynes/cm^2[1]. (Fig. 1).

(ii) In He II, there is an order of magnitude difference between the visible and audible cavitation thresholds. Whereas no distinction is observed for He I.[2] (Fig. 2).

(iii) In He II, the incipient visible cavitation threshold, i.e. the sound pressure amplitude required to initiate visible cavitation, is greater than the desinent threshold, i.e. the minimum pressure that is needed to maintain the visible cavitation.[3] (Fig. 2).

(iv) The audible threshold in He II is reduced, when the liquid is subject to rotation. The reduction commences when the rotating speed exceeds the value corresponding to the creation of one unit of quantized vortices. No such reduction is observed in He I[4][5].

The questions implied in these experimental findings are many. In the following, we shall attempt to construct a theory which can at least qualitatively account for all these puzzling phenomena.

II. The "Nuclei"

The maximum theoretical tensile strength that would be expected from the Van der Waals forces between atoms, is about 10^7 dynes/cm^2 for liquid helium(6). Yet the tensile strength as measured by Beams(7) using the spinning capillary method is about two orders of magnitude smaller, whereas the cavitation threshold, even for the incipient visible cavitation, is about three orders of magnitude smaller. The usual explanation of these discrepancies is that there are nuclei in the liquid. To account for the observed values of the cavitation thresholds, nuclei of radii 3×10^{-4} cm are needed to overcome the surface tension, if audible threshold is our concern(8). Even for incipient visible cavitation threshold, we would need nuclei with radii about 10^{-5} cm. The requirement for the existence of cavitation nuclei is not unique for liquid helium. For ordinary liquids, we also need to assume the existence of nuclei of similar sizes to account for the discrepancy between the cavitation thresholds and the theoretical tensile strength. There the nuclei are supposed to be suspended solid particles, gas pockets stabilized in cracks, or thermal spikes created by cosmic rays. The problem of cavitation nuclei in ordinary liquids is by no means fully understood. We can only claim that under certain circumstances, those agents just mentioned do play a role to enhance the cavitation. However for liquid helium, it is very doubtful they can play similar roles.

At the temperature of liquid helium, no other substance can exist in the gaseous state, except He^4 itself or its rare isotope He^3. Liquid helium is a very light liquid with a density about 0.14 gm/cm^3, and it is also known to be a very good wetting agent. Therefore it is not likely there would be enough suspended solid particles to serve as cavitation nuclei under the normal circumstance. The effect of cosmic rays may not be as readily ignored. However, we could say that the thermal aspect of its effect is minimal for He II due to the extremely high efficiency of the heat transfer.

Now, the problem of cavitation nuclei could be approached from a different angle in the light of the new interpretation of rotons[9]. According to this new interpretation rotons are considered to behave like tiny quantized vortex rings. Among other properties, there is tension in the vortex core, given approximately by

$$T \approx \frac{\rho k^2}{4\pi}$$

where ρ is the density of the liquid and k is the circulation around the vortex core. For one quantum of circulation, $k = \frac{h}{m} \approx 10^{-3}\ \mathrm{cm^2 sec^{-1}}$, and $T \approx 10^{-8}$ dynes, which is of the same order of magnitude as the Van der Waals force in the liquid helium. It is to be stipulated that the Van der Waals force is somewhat larger than the vortex tension to prevent the spontaneous rupture of the liquid by the vortex tension. The spontaneous rupture does occur when the boiling point is reached.

The reason that the spontaneous rupture occurs at the boiling point is that the majority of the rotons start to acquire enough quanta of circulation, say n quanta, so that their tension in the vortex core exceeds the Van der Waals force. Below the boiling point, there is practically no rotons with n quanta. The liquid, in the first place, cannot maintain those n-rotons, and dynamical considerations will prevent its occurrence during the formation stage. In some sense, the n-rotons in the liquid can be considered as holes like those discussed by Fürth[10]. They form and disappear, never stable. But we could define a distribution function for those holes at any given instant. The relative number of these holes is very small except in the neighborhood of the boiling point.

Below the boiling point, the stable rotons are those with (n-1) quanta or less. The boiling point, i.e. the point of inception of massive vaporization, is due to the overpopulation of the (n-1)-rotons caused by the increase of temperature. The tensile strength of the liquid then is controlled by these (n-1)-rotons, and their locality are where the nuclei of cavitation are generated.

III. Cavitation in He I

The tension in (n-1)-rotons is smaller than the Van der Waals force, yet comparable. Their difference may be much smaller than the Van der Waals force. This residue force we take to represent essentially the tensile strength of the liquid. This also accounts for the audible cavitation threshold of the liquid. The tension due to imposed sound field may cause the formation of tiny bubbles by the rupture of the liquid. These original bubbles, with radius R_o, will grow bigger with the aid of cosmic rays. Their subsequent collapse will give rise to noises identifiable with cavitation.

For He I, the energy deposited in the local region around the original bubble, i.e. the thermal spike, as it was called by Seitz[11], will enable the bubble to grow to a radius about 3×10^{-4} cm or more. At $R_c = 3 \times 10^{-4}$ cm, the audible threshold of 2,000 dyne/cm^2 is sufficient to overcome the pressure due to the surface tension $2\sigma/R_c$, and visible cavitation appear. Therefore, with the aid of cosmic rays there is no distinction between audible and visible cavitation threshold in He I.

In order that the thermal spike, with radius R_o can grow to a bubble with radius $R_c = 3 \times 10^{-4}$ cm, it is necessary that the time for dynamic growth t_g is smaller than the time of heat escape t_e.

The value t_e can be estimated as

$$t_e = \frac{R_c^2}{4D} \quad , \tag{1}$$

where D is the thermal diffusivity. Taking the thermal conductivity as 5×10^{-5} cal./deg.-cm.-sec. the specific heat as 0.6 cal./g.-deg. and density as 0.14 g./cm^3, we obtain $D = 6 \times 10^{-4}$ cm^2/sec. Thus

$$t_e \approx 4 \times 10^{-5} \text{ sec.}$$

The value t_g may be estimated from the model of a uniformly expanding sphere in an incompressible liquid[11]. Since $\frac{R_c}{R_o} \gg 1$, t_g should lie between

$$t_g^{(1)} = \left(\frac{3}{2}\right)^{\frac{1}{2}} \frac{R_c}{c_o} \quad , \tag{2}$$

and

$$t_g^{(2)} = \left[\frac{6(\gamma-1)}{25}\right]^{\frac{1}{2}} \left(\frac{R_c}{R_o}\right)^{3/2} \frac{R_c}{c_o} \tag{3}$$

where $c_o^2 = \frac{p_o}{\rho}$, and p_o is the initial pressure. $t_g^{(1)}$ is obtained on the assumption that the internal pressure of the expanding sphere is constant; while $t_g^{(2)}$ is obtained on the assumption that the internal pressure p varies according to the relation

$$p = p_o \left(\frac{R_o}{R}\right)^{3\gamma} \quad . \tag{4}$$

With p_o taken to be of the order of atmospheric pressure, and $\gamma = \frac{5}{3}$, we obtain

$$t_g^{(1)} \approx 10^{-7} \text{sec.} \quad ,$$

and

$$t_g^{(2)} \approx 10^{-7}\left(\frac{R_c}{R_o}\right)^{3/2} \text{ sec.}$$

It is evident that $t_g^{(1)}$ can meet our requirement very well, while $t_g^{(2)}$ will be too big if R_o is smaller than 1/50 of R_c. How big is R_o? Each individual roton can have linear dimension of about 10^{-7} cm, but holes much bigger can be produced due to coalescence of many ruptured rotons. Also since evaporation is continuously taking place to fill the growing bubble with additional vapor, while the liquid region surrounding the thermal spike is in a superheated state due to the interaction with the cosmic ray, the pressure inside the bubble may not decrease as drastically as given by (4) during its growth. Still, for a working hypothesis, let us take $R_o = 10^{-5}$ cm.

The bubbly behavior of He I under normal circumstance is due to the superheated state of the liquid. There the "nuclei" are the holes created by the n-rotons. Cosmic rays may again help them to reach the critical radii for boiling. These vapor-filled thermal bubbles of radii of the order of 10^{-4} cm to 10^{-3} cm can also serve as the nuclei for the visible cavitation. This could explain the observation in He I that cavitation bubbles are often seen before they become audible[5].

IV. Cavitation in He II

The mechanisms for cavitation in He II are essentially the same as those for He I. There are, however, two main differences:

(i) The heat transfer in He II is controlled by the internal convection and is much more efficient than the thermal conduction in He I.

(ii) Not all the helium atoms partake in excitations to form rotons, so there is room for the creation of new excitations.

We can immediately see how the novel features of cavitation in He II can now be accounted for.

The audible cavitation threshold of He II is about the same as that of He I, since it is also due to the rupture of the (n-1)-rotons. We again have tiny bubbles of radius R_o formed. They may again grow somewhat bigger with the aid of cosmic rays. Their subsequent collapse will yield the audible noises.

Now since the internal convection is much more efficient than the thermal conduction, the time for heat escape in He II will usually be much shorter than that in He I. The heat transported by internal convection is essentially transmitted at the speed of the second sound c_2. Therefore we may estimate t_e as

$$t_e = \frac{R_c}{c_2} \quad ,$$

where R_c is now the critical radius of the nucleus for incipient visible cavitation.

We may note that $c_2 \approx 2 \times 10^3$ cm/sec for $0.9°K < T < 1.8°K$, while c_o has about the same value as c_2. From (3), we see that if the growth time t_g is to be kept smaller than t_e, R_c cannot be much bigger than R_o. This means the heat deposited by cosmic rays is not of much help for the enlargement of the nucleus bubble. This is also reasonable considering that the heat pulse is propagating outward with about the same speed as that of the expanding bubble wall, so not much heat in the surrounding region can be trapped within the nucleus bubble. Let us again take $R_o \approx 10^{-5}$ cm, allow a 50% increase due to the interaction with cosmic rays, we then have

$$R_c = 1.5 \times 10^{-5} \text{ cm}.$$

The incipient visible threshold pressure is now

$$p_t = \frac{2\sigma}{R_c} = 4 \times 10^4 \text{ dyne/cm}^2 \quad ,$$

which is about 20 times that of the audible threshold as shown in Fig. 2.

The mechanism of rectified internal convection[8] will take over when the temperature is high enough so that $2\sigma/R_c$ is no longer dominating over the vapor pressure. This will not happen until the temperature is about 2°K. Then the threshold pressure will be diminished somewhat.

The major reason that the incipient visible cavitation threshold decreases from a relative amplitude of 220 to 1.8°K to about 40 as T_λ is approached is due to the corresponding rapid decrease of the speed of second sound. We may note that at T = 1.8°K, $c_2 = 1.978 \times 10^3$ cm/sec. while at T = 2.176°K, $c_2 = 3.12 \times 10^2$ cm/sec. The decrease of c_2 will cause the proportional increase of t_e and t_g, and consequently the proportional increase of R_c, until at T_λ when the thermal conduction takes over from the internal convection as the principal mode of heat transfer. Then the visible threshold merges with that of He I.

The cavitation bubble of visible size is rather empty. During the rapid growth due to the negative pressure of oscillation, the amount of vaporization cannot catch up with the dynamic process. We need the knowledge of the accommodation coefficient[12] to estimate the pressure of the vapor inside the cavitation bubble. But one thing is fairly certain, the larger the amplitude of the pressure oscillation to cavitate, the larger will be the resulting cavitation bubble, and the more rarefied is the vapor inside the cavitation bubble. Consequently the more violent will be the subsequent collapse. The collapse phase is very complex. The bubble may very well break up due to instability before the dynamical collapsing limit is reached[12]. The remnants of the collapsing bubble is expected to be smaller the more violent is the collapsing process. The size of the remnants of the collapsing bubble depends also on the vapor content of the nucleus bubble. The incipient nucleus bubble is likely in an overpressured state due to the relative small t_e. We suggest the size of the resulting remnants of the collapsing bubble will be somewhat larger than the incipient nucleus bubble. These remnants then serve as nucleus bubbles for the desinent cavitation. The desinent nucleus bubbles, contrary to the incipient nucleus bubbles, are not overpressured. The desinent cavitation threshold is one for which the collapse remnants are of the same size as the nucleus bubbles. As t_e gets larger and larger, we expect the incipient nucleus bubble is less and less overpressured, and the size difference between the incipient and desinent nucleus bubbles become smaller and smaller. Thus in He I, the distinction between incipient and desinent cavitation threshold is not observed as markedly at all.

Beaubouef et al[13] has given another explanation of the distinction between the incipient and desinent cavitation thresholds based on the theory of rectified internal convection. They have a quite satisfactory qualitative picture. The theory of rectified internal convection can be improved by taking into account of the nonlinear effects. Then the quantitative discrepancy may not be as serious. Their theory will apply to cases that visible bubbles are executing oscillations more or less steadily; whereas the picture we just presented applies to cases that bubbles grow and collapse continuously in a relatively violent manner.

We have stated that the audible thresholds are related to the rupture of the liquid resulting from the break-up of the rotons. We should remark that the tension in the vortex core as given by (1) is only approximate. The tension actually is a slowly increasing function of the radius of the vortex ring[9]. Therefore, if we have particularly large rotons present in the liquid, the negative pressure needed to break up those rotons will be less. The reduction of audible cavitiation threshold in He II when the liquid is under rotation can then be satisfactorily explained as follows. When the rotating speed exceeds the value corresponding to one quantum of circulation, vortex rings, i.e. large rotons are shed from the shaft's end. Since it is relatively easier to break these large rotons, the audible threshold is lowered. The existence of these large rotons depends on the availability of the unexcited helium atoms in He II. In He I, no unexcited helium atoms are left[9]. Hence no new quantized vortex rings may be created by rotation, and we do not have the reduction of cavitation threshold. That the reduction of threshold appears with the production of vortices with one quantum of circulation leads us to conclude that $n = 2$, i.e. liquid helium consists essentially of rotons with one quantum of circulation.

The audible threshold, as a function temperature, has a sharp peak at T_λ. This peak is closely related to the nature of λ-transition. The λ-point, besides being the lowest temperature at which all helium atoms are excited, also marks an order-disorder transition. The order refers to the arrangements and orientations of the rotons[9]. The anomaly of the specific heat at T_λ tells that a substantial portion of the absorbed energy has to be spent on the destruction of the order before it can contribute to the kinetic motion. The process of breaking up the rotons, which inevitably involves the energy absorption, then would also require extra work if it is coupled with the destruction of order. It is interesting to note that the half width in temperature of the threshold peak is of the same order as that of the specific heat curve[14].

V. Discussion

The essence of the present theory is the existence of a weaker bond between atoms than the Van der Waals force. It so happens that the new interpretation of rotons fits quite well for this purpose. However, the λ-point anomaly of the audible threshold, and the reduction of audible threshold in He II by rotation, which is explainable by the present theory, will not follow from the mere existence of weak bonds between atoms. In constructing the complete picture of the cavitation phenomena in liquid, we have relied on the help of external agents like cosmic rays. Experiments under conditions that cosmic rays may be largely shielded off would yield valuable information for the understanding of the problem. The number of rotons decreases with temperature. At low enough temperature when the population of excitations is dominated by the phonons rather than by the rotons, the nature of cavitation may be drastically different. This is also an interesting area worth our effort to explore.

As we know, aside from having very low temperature, He I behaves just like other ordinary liquids. Therefore if roton theory may apply to He I, it may also be applicable to other liquids. Of course, the predominant rotons are expected to have more than one quantum of circulation. But the general picture as we have constructed for He I may still be valid. It is likely that the problems concerning the low tensile strength, and the nuclei of cavitation of ordinary liquids could be resolved by an analogous roton theory.

References

1. R. D. Finch, R. Kagiwada, M. Barmatz, and I. Rudnick, Phys. Rev. A134, 1425 - 1428 (1964).
2. R. D. Finch and T. G. J. Wang, J. Acoust. Soc. Am. 39, 511 - 514 (1966).
3. P. D. Jarman and K. J. Taylor, J. Acoust. Soc. Am. 39, 584 - 585 (1966).
4. R. D. Finch and M. L. Chu Jr., Phys. Rev. 161, 202 - 206 (1967).
5. M. L. Chu, Jr., Ph.D. Dissertation, Dept. of Mech. Eng., Univ. Of Houston, Houston, Tex. (1967).
6. F. London, "Superfluids", (Dover Publications, Inc. New York, 1964), Vol. II, pp. 21 - 25.
7. J. W. Beams, Phys. Rev. 104, 880 - 882 (1956).
8. D. Y. Hsieh, "Rectified Internal Convection and Ultrasonic Cavitation in Helium II," Rep. No. 85-33, Div. of Eng. and App. Science, Calif. Inst. of Tech. (1966).
9. D. Y. Hsieh, "A Physical Model of Liquid Helium," Rep. No. 85-43, Div. of Eng. and App. Science, Calif. Inst. of Tech. (1968).
10. R. Fürth, Proc. Cambridge Phil. Soc. 37, 252 - 275, 276 - 280 (1941).
11. F. Seitz, Phys. of Fluids, 1, 2 - 13 (1958).
12. M. S. Plesset, in "Cavitation in Real Liquids," R. Davies, Ed. (Elsevier Pub. Co. New York, 1964) pp. 1 - 18.
13. R. T. Beaubouef, M. L. Chu, A. Mosse, and R. D. Finch, J. Acoust. Soc. Am., 42, 1153 (1967).
14. R. D. Finch, T. G. J. Wang, R. Kagiwada, M. Barmatz, and I. Rudnick, J. Acoust. Soc. Am. 40, 211 - 218, (1966).

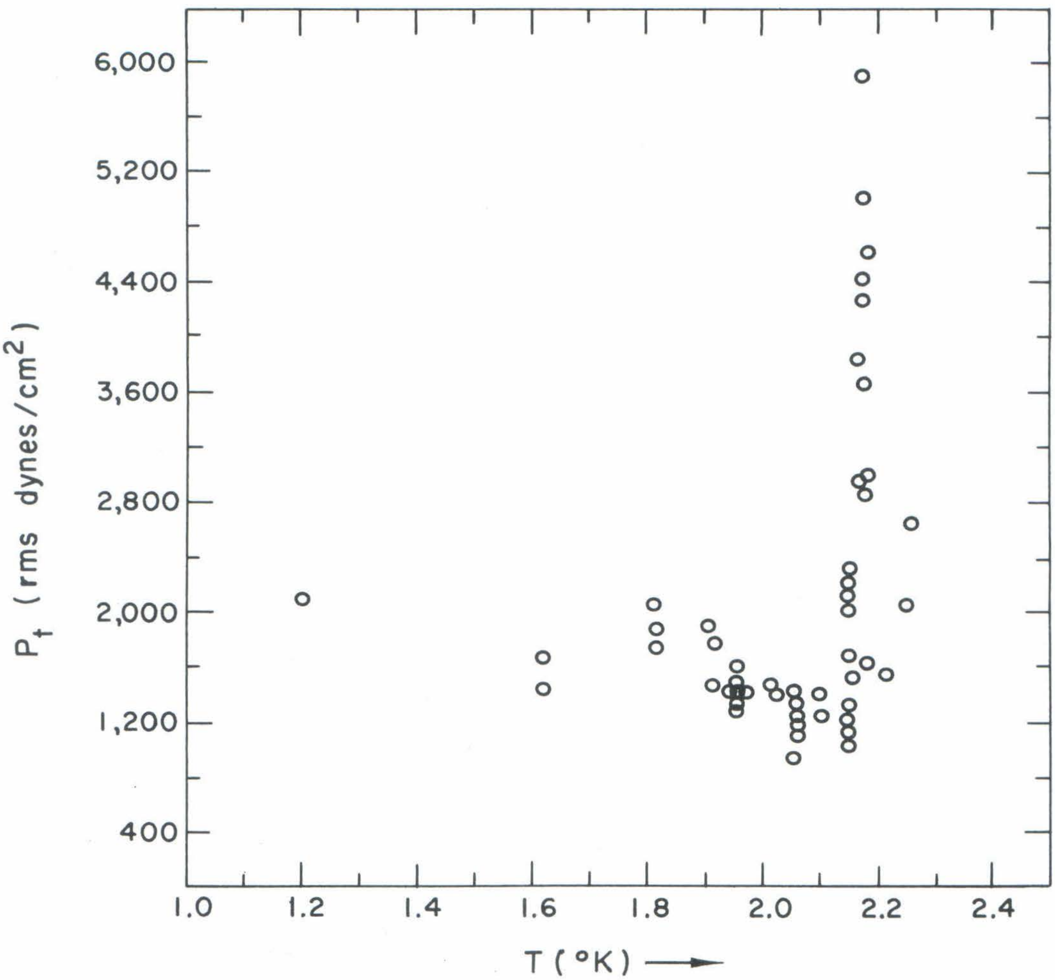

FIG. I CAVITATION THRESHOLDS
REF. (I)

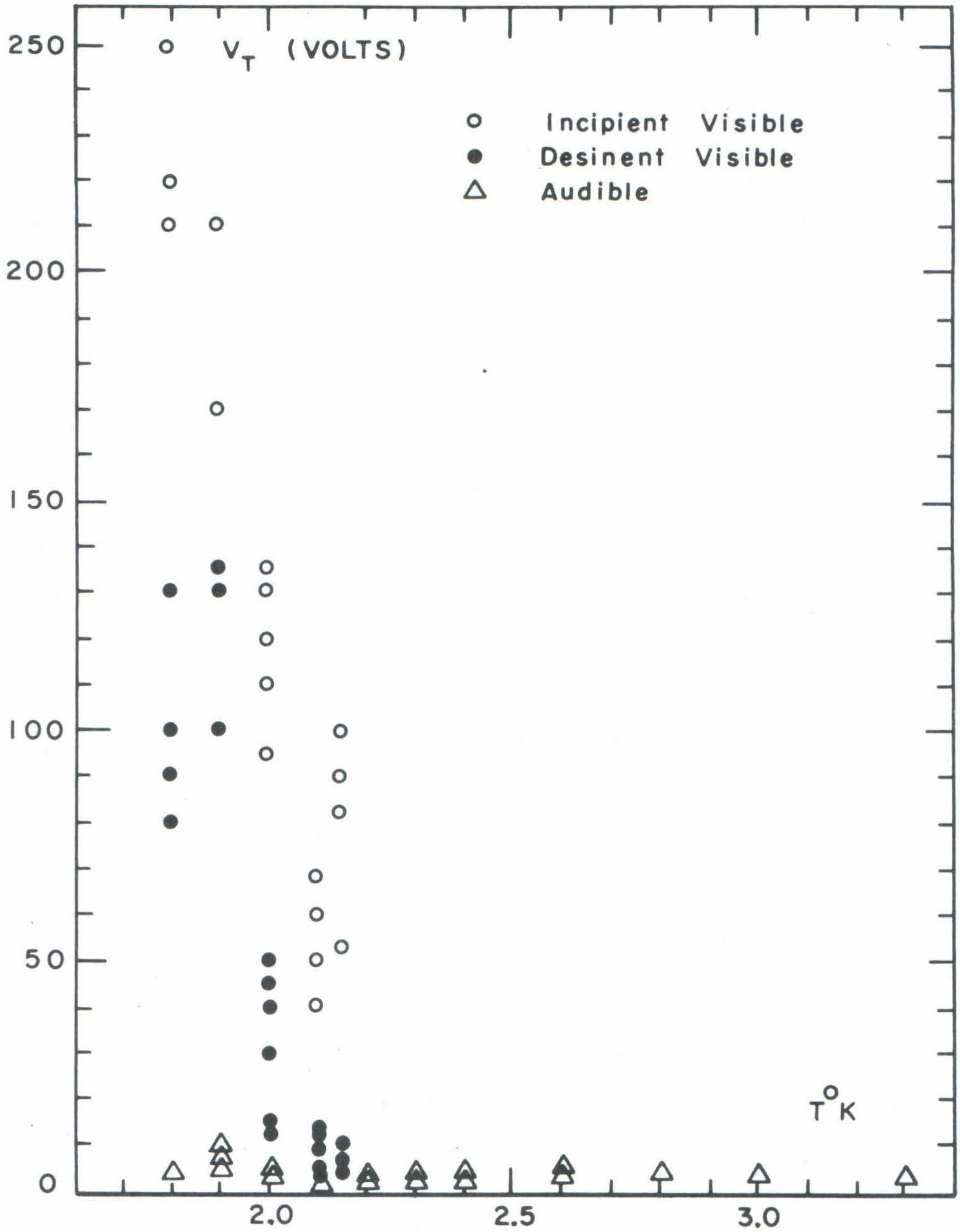

Fig. 2 Dependence of Incipient and Desinent Thresholds on Temperature. Ref.(5)

DISTRIBUTION LIST FOR UNCLASSIFIED TECHNICAL REPORTS

ISSUED UNDER

CONTRACT N00014-67-0094-0009
(Single copy unless otherwise specified)

Officer in Charge
Annapolis Division
Naval Ship Research & Development Center
Annapolis, Maryland 21402

Commander
Boston Naval, Shipyard
Boston, Mass. 02129

Commanding Officer
Office of Naval Research Branch Office
495 Summer Street
Boston, Mass. 02210

Commanding Officer & Director
Naval Applied Science Lab.
Naval Base, Attn: Code 930
Brooklyn, New York 11252

Naval Applied Sci. Lab.
Technical Library
Building 1, Code 222
Flushing & Washington Aves.
Brooklyn, N. Y. 11251

Commanding Officer
NROTC and Naval Administrative Unit
Mass. Inst. of Technology
Cambridge, Mass. 02139

Department of Naval Architecture
and Marine Engineering
Room 5-228
Massachusetts Inst. of Technology
Cambridge, Massachusetts 02139

Commander
Charleston Naval Shipyard
U. S. Naval Base
Charleston, S. C. 29408

Commander
Naval Weapons Center
China Lake, California 93555

Commanding Officer
Office of Naval Research Branch Office
219 South Dearborn St.
Chicago Ill. 60604

Commander
Naval Weapons Laboratory
Attn. Technical Library
Dahlgren Va. 22418

Commander
Naval Weapons Laboratory
Attn: Computation & Analysis Lab.
Dahlgren, Virginia 22448

Commanding Officer
Army Research Office
Attn: ESD - AROD
Box CM, Duke Station
Durham, North Carolina 27706

Commanding Officer
Army Research Office
Box CM, Duke Station
Durham, North Carolina 27706

Commanding General
Army Engineering R & D Labs.
Tech. Documents Center
Fort Belvoir, Virginia 22060

Commander
Long Beach Naval Shipyard
Long Beach, Calif. 90802

Commanding Officer & Director
Underwater Sound Lab.
Fort Trumbull
Attn: Technical Library
New London, Conn. 06321

Commanding Officer
USN Underwater Weapons and
Research & Engrg Station
Attn: Technical Library
Newport, Rhode Island 02840

Office of Naval Research
New York Area Office
207 W. 24th St.
New York, N. Y. 10011

Commanding Officer
Office of Naval Research Branch Office (25)
Box 39
FPO New York, N. Y. 09510

Commander
Naval Undersea Warfare Center
3203 E. Foothill Blvd.
Pasadena, California 91107

Commanding Officer
Office of Naval Research Branch Office
1030 E. Green St.
Pasadena, Calif. 91101

Commander
Technical Lib. (Code 249b)
Philadelphia Naval Shipyard
Philadelphia, Pa. 19112

Commander
Naval Missile Center
Attn: Technical Library
Point Mugu, Calif. 93041

Commanding Officer & Director
Naval Civil Engineering Lab.
Port Hueneme, Calif. 93041

Commander
Portsmouth Naval Shipyard
Portsmouth New Hampshire 03801

Commander
Norfolk Naval Shipyard
Portsmouth, Virginia 23709

Commander
Naval Command Control Communications
Laboratory Center
San Diego, California 92152

Commander (Code 246P)
Pearl Harbor Naval Shipyard
Box 400
FPO San Francisco 96610

Office of Naval Research
San Francisco Area Office
1076 Mission St.
San Francisco, Calif. 94103

Commander
Naval Ordnance Laboratory
Attn: Dr. A. May
White Oak
Silver Spring, Md. 20910

Commander
Naval Ordnance Laboratory
Attn: Dr. A. E. Seigel
White Oak Laboratory
Silver Spring, Md. 20910

Commander
Naval Ordnance Laboratory
Attn: Gas Dynamics Division
White Oak
Silver Spring, Md. 20910

Commander
Naval Ordnance Laboratory
Attn: Librarian
White Oak
Silver Spring, Md. 20910

Commander
Naval Ordnance Laboratory
Attn: Chief, Lib. Div.
White Oak
Silver Spring, Md. 20910

Commanding Officer & Director
Naval Ship Research & Development Center
Washington, D. C. 20007

Commander
Naval Ship Systems Command
Department of the Navy
Attn: Code 6340
Washington, D. C. 20360

Director
U. S. Naval Research Laboratory
Attn: Code 2027 (6)
Washington, D. C. 20390

Chief of Naval Research
Department of the Navy
Attn: Code 438 (3)
Washington, D. C. 20360

Commanding Officer & Director
N. S. R. D. C.
Attn: Code 513
Washington, D. C. 20007

Commander
Naval Ship Systems Command
Attn: Code 6440
Washington, D. C. 20360

Commander
Naval Ship Engr. Center
Concept Design Division
Attn: Code 6420
Washington, D. C. 20360

Commanding Officer & Director
N. S. R. D. C.
Attn: Code 800
Washington, D. C. 20007

Commanding Officer & Director
N. S. R. D. C.
Attn: Code 581
Washington, D. C. 20007

Commanding Officer & Director
N. S. R. D. C.
Attn: Code 550
Washington, D. C. 20007

Commander
Naval Ship Systems Command
Department of the Navy
Attn: Code 6442
Washington, D. C. 20360

Commander
Naval Ship Systems Command
Department of the Navy , Attn: Code 6342A
Washington, D. C. 20360

Commanding Officer & Director
N. S. R. D. C.
Attn: Code 108
Washington, D. C. 20007

Commander Naval Air Systems Command
Department of the Navy
Attn: Code Air 370
Washington, D. C. 20360

Chief of Naval Research
Department of the Navy
Attn: Code 463
Washington, D. C. 20360

Commanding Officer & Director
N. S. R. D. C.
Attn: Code 901
Washington, D. C. 20007

Commanding Officer & Director
N. S. R. D. C.
Attn: Code 940
Washington, D. C. 20007

Commanding Officer & Director
N. S. R. D. C.
Attn: Code 942
Washington, D. C. 20007

Commanding & Director
N. S. R. D. C.
Attn: J. L. Power (589)
Washington, D. C. 20007

Commanding Officer & Director
N. S. R. D. C.
Attn: Code 520
Washington, D. C. 20007

Commander
Naval Ship Systems Command
Department of the Navy
Attn: Code 0341
Washington, D. C. 20360

Commander
Naval Ship Systems Command
Department of the Navy
Attn: Code 6345
Washington, D. C. 20360

Commanding Officer & Director
N. S. R. D. C.
Attn: Code 500
Washington, D. C. 20007

Commander
Naval Ordnance Systems Command
Attn: ORD 03
Washington, D. C. 20360

Commander
Naval Ordnance Systems Command
Attn: ORD 913 (Library)
Washington, D. C. 20360

Commander
Naval Ordnance Systems Command
Attn: ORD 05411
Washington, D. C. 20360

Commander
Naval Ship Systems Command
Department of the Navy
Attn: Code 61500
Washington, D. C. 20360

Commanding Officer and Director
N. S. R. D. C.
Attn: Code 526A
Washington, D. C. 20007

Chief of Naval Research
Department of the Navy
Attn: Code 429
Washington, D. C. 20360

Commanding Officer & Director
N. S. R. D. C.
Attn: Code 521
Washington, D, C. 20007

Commander
Naval Ship Engineering Center
Concept Design Division
Attn: Code 6110
Washington, D, C. 20360

Commander
Naval Ship System Command
Technical Library, Code 2021
Washington, D. C. 20360

Superintendent
Naval Postgraduate School
Attn: Library
Monterey, Calif. 93940

United States Atomic Energy Commission
Div. of Technical Info. Extension
P. O. Box 62
Oak Ridge, Tennessee 37830

National Academy of Sciences
National Research Council
2101 Constitution Ave., N. W.
Washington, D. C. 20360

Director, Engineering Science Division
National Science Foundation
Washington, D. C. 20550

Director of Research Code RR
National Aeronautics & Space Admin.
600 Independence Ave., S. W.
Washington, D. C. 20546

Division of Engineering
Maritime Administration
441 G. Street, N. W.
Washington, D. C. 20235

Division of Ship Design
Maritime Administration
441 G. Street, N. W.
Washington, D. C. 20235

Commander, R & T Divisions
Air Force Systems Command
Attn: L. M. Medgepeth (APIP- 1)
Wright-Patterson AFB, Ohio 45433

AFOSR (SREM)
1400 Wilson Boulevard
Arlington, Va. 22209

National Science Foundation
Engineering Division
1800 G. Street, N. W.
Washington, D. C. 20550

Defence Research & Dev. Attache
Australian Embassy
1735 Eye Street, N. W.
Washington, D. C. 20006

Superintendent
Naval Academy
Attn: Library
Annapolis, Md. 21402

Defense Documentation Ctr.
Cameron Station
Alexandria, Virginia 22314 (20)

Dr. R. E. Wilson
Assoc. Tech. Dir. (Aeroballistics)
Naval Ordnance Laboratory
White Oak
Silver Spring, Md. 20910

Librarian
Department of Naval Architecture
University of California
Berkeley, California 94720

Engineering Library
Plant 25
Grumman Aircraft Engineering Corp.
Bethpage, Long Island, N. Y. 11714

NASA Lewis Research Center
Attn: Library MS 60-3
21000 Brookpark Road
Cleveland, Ohio 44135

Technical Library
Webb Institute of Naval Architecture
Glen Cove, Long Island, N. Y. 11542

Lorenz G. Straub Library
St. Anthony Falls Hydraulic Lab.
Missippi River At 3rd Ave., S. E.
Minneapolis, Minnesota 55414

Engineering Societies Library
345 East 47th Street
New York, N. Y. 10017

NASA, Langley Research Center
Langley Station
Attn: Library MS 185
Hampton, Virginia 23365

National Research Council
Aeronautical Library
Attn: Miss O. M. Leach, Librarian
Montreal Road
Ottawa 7, Canada

Redstone Scientific Information Center
Attn: Chief, Document Section
Army Missile Command
Redstone Arsenal, Alabama 35809

Tech. Library, Code H245C-3
Hunters Point Division
San Francisco Bay Naval Shipyard
San Francisco, California 94135

Fenton Kennedy Document Library E
The Johns Hopkins University
Applied Physics Laboratory
8621 Georgia Ave.
Silver Spring, Maryland 20910

Engineering Library
Dept. 218, Bldg 101
MC Donnel Aircraft Corp.
P.O. Box 516
St. Louis, Missouri 63166

Shipyard Technical Library
Code 130L7 Bldg. 746
San Francisco Bay Naval Shipyard
Vallejo, California 94592

Library
The Marquardt Corporation
16555 Saticoy
Van Nuys, California 91409

Science & Technology Division
Library of Congress
Washington, D. C. 20540

Librarian Station 5-2
Coast Guard Headquarters
1300 E. Street, N. W.
Washington, D. C. 20226

NASA Scientific & Tech. Info. Fac.
Attn: Acquisitions BR (S-AK/DL)
P.O. Box 33
College Park, Maryland 20740

Library
Aerojet-General Corp.
6352 N. Irwindale Ave.
Azusa, California 91702

The Bonker-Ramo Corporation
Attn: Technical Library
8433 Fallbrook Ave.
Canoga Park, California 91804

Professor L. N. Milne-Thomson
Mathematics Department
University of Arizona
Tucson, Arizona 85721

Professor Finn C. Michelson
Naval Architecture & Marino Engineering
450 West Engineering Building
University of Michigan
Ann Arbor, Michigan 48106

Dr. E. J. Skudrzyk
Ordnance Research Laboratory
Pennsylvania State University
University Park, Pennsylvania 16801

Dr. C. S. Yih
Department of Engineering Mechanics
University of Michigan
Ann Arbor, Michigan 48108

Professor F. G. Hammitt
University of Michigan
Ann Arbor, Michigan 48108

Professor A. Kuethe
Dept. of Aeronautical Engineering
University of Michigan
Ann Arbor, Michigan 48108

Dr. R. B. Bouch
General Dynamics
Quincy Division
97 E. Howard
Quincy, Mass. 02169

Dr. J. Menkes
Institute for Defense Analyses
400 Army-Navy Drive
Arlington, Virginia 22204

Prof. W. W. Willmarth
Dept. of Aero/space Engineering
University of Michigan
Ann Arbor, Michigan 48104

Professor J. Foa
Dept. of Aeronautical Engineering
Rennsselaer Polytechnic Institute
Troy, New York 12180

Professor R. C. Di Prima
Department of Mathematics
Rennsselaer Polytechnic Institute
Troy, New York 12180

Dr. M. Sevik
Ordnance Research Laboratory
Pennsylvanis State University
University Park, Pa. 16801

Dr. J. M. Robertson
Dept. of Theoretical & Applied Mechanics
University of Illinois
Urbana, Illinois 61803

Professor J. K. Vennard
Dept of Civil Engineering
Stanfo rd Unviersity
Stanford, California 94305

Dr. G. F. Wislicenus
Ordnance Research Laboratory
Pennsylvania State University
University Park, Pennsylvania 16801

Dr. Byrne Perry
Department of Civil Engineering
Stanford University
Stanford, California 94305

Professor E. Y. Hsu
Dept. of Civil Engineering
Stanford University
Stanford, California 94305

Professor D. Gilbarg
Stanford University
Stanford, California 94305

School of Applied Mathematics
Indiana University
Bloomington, Indiana 47401

Mr. J. M. Wetzel
St. Anthony Falls Hydraulic Lab.
University of Minnesota
Minneapolis, Minnesota 55414

Professor J. Ripkin
St. Anthony Falls Hydraulic Lab.
University of Minnesota
Minneapolis, Minnesota 55414

Professor M. V. Morkvin
Aeronautics Building
Johns Hopkins University
Baltimore, Maryland 21218

Director
Scripps Institution of Oceanography
University of California
La Jolla, California 92037

Professor A. F. Charwat
Department of Engineering
University of California
Los Angeles, California 90024

C. E. Bowers (2)
St. Anthony Falls Hydraulic Lab.
University of Minnesota
Minneapolis, Minnesota 55414

Professor A. Charnes
The Technological Institute
Northwestern University
Evanston, Illinois 60201

Dr. O. Grim
Institute fur Schiffbau
Lammersieth 90
2, Hamburg 33, Germany

Dr. S. F. Hoerner
148 Busteed Drive
Midland Park, New Jersey 07432

Mr. D. Savitsky
Stevens Institute of Technology
Davidson Laboratory
Hoboken, New Jersey 07030

Mr. J. P. Breslin
Stevens Institute of Technology
Davidson Laboratory
Hoboken, New Jersey 07030

Dr. John E. Mayer, Jr.
Research & Engineering Center
Ford Motor Company
P.O. Box 2053
Dearborn, Michigan 48123

C. A. Gongwer
Aerojet General Corporation
9100 E. Flair Drive
El Monte, California 91734

J. D. Malloy, President
Hydrosystems, Inc.
19 Engineers Lane
Farmingdale, New York 11735

Mr. J. Z. Lichtman, Code 937
Naval Applied Science Lab.
Brooklyn, New York 11251

Dr. Ronald Smelt
Vice President & Chief Scientist
Lockheed Aircraft Corporation
Burbank, California 91503

Dr. H. Reichardt, Director
Max Planck Institut fur Stromungsforschung
Bottingerstrasse 6-8
Gottingen, Germany

Dr. H. W. Lerbs
Hamburgische Schiffbauversuchsanstalt
Bramfelder Strasse 164
Hamburg 33, Germany

Dr. H. Schwaneche
Hamburgische Schiffbauversuchsanstalt
Bramfelder Strasse 164
Hamburg 33, Germany

DIPL. Ing. A Gross
Versuchsanstalt fur Wasserbau & Schiffbau
Schleuseninsel IM Tiergarten
Berlin, Germany

Professor Dr.-Ing. S. Schuster
Versuchsanstalt fur Wasserbau & Schiffbau
Berlin, Germany

Dr. K. Eggers
Instiut fur Schiffbau
University of Hamburg
Laemmersieth 90
2 Hamburg 33, Germany

Prof. Dr. Ir. J.D. Van Manen
Netherlands Ship Model Basin
Haagsteeg 2, Postbox 28
Wageningen, The Netherlands

Professor W. R. Sears
4927 Pacifica Drive
San Diego, California 92109

Professor F. Zwicky
Department of Physics
California Institute of Technology
Pasadena, California 91109

Professor A. Ellis
University of Calif. San Diego
La Jolla, Calif. 92037

Professor J. M. Killen
St. Anthony Falls Hydraulic Lab.
University of Minnesota
Minneapolis, Minnesota 55414

Professor A. G. Strandhagen
Department of Engineering Mechanics
University of Notre Dame
Notre Dame, Indiana 46556

Professor A. Peters
Institute of Mathematical Sciences
New York University
251 Mercer Street
New York, New York 10003

Professor R. E. Little
University of Michigan Dearborn Campus
4901 Evergreen Road
Dearborn, Michigan 48128

Professor John Laufer
Dept. of Aerospace Engineering
University Park
Los Angeles, California 90007

Dr. Martin H. Bloom
Polytechnic Institute of Brcoklyn
Graduate Center, Dept. of Aerospace
Eng. & Applied Mechanics
Farmingdale, N. Y. 11735

Professor J. J. Foody
Chairman, Engineering Department
State University of New York
Maritime College
Bronx, New York 10465

Professor John Miles
% I. G. P. P.
University of Calif. San Diego
La Jolla, Calif. 92038

Professor T. Y. Wu
California Insitute of Technology
Pasadena, California 91109

Mr. C. S. Song
St. Anthony Falls Hydraulic Lab.
University of Minnesota
Minneapolis, Minnesota 55414

Professor M. A. Abkowitz
Dept. of Naval Architecture and
Marine Engineering
Massachusetts Inst. of Technology
Cambridge, Massachusetts 02139

Professor M. S. Uberoi
Department of Aeronautical Engineering
University of Colorado
Boulder, Colorado 80303

Professor G. L. Von Eschen
Dept. of Aeronautical Astronautical Engrg.
Ohio State University
Columbus, Ohio 43210

Professor R. F. Probstein
Department of Mechanical Engineering
Massachusetts Inst. of Technology
Cambridge, Massachusetts 02139

Professor A. T. Ippen
Massachusetts Inst. of Technology
Cambridge, Massachusetts 02139

College of Engineering
Office of Research Services, Univ. of Calif.
Berkeley, California 94720

Professor M. Holt
Division of Aeronautical Sciences
University of California
Berkeley, California 94720

Prof. J. V. Wehausen
Department of Naval Architecture
University of California
Berkeley, California 94720

Professor G. Birkhoff
Harvard University
Cambridge, Massachusetts 02138

Dr. E. E. Sechler
Executive Officer for Aero.
California Institute of Technology
Pasadena, California 91109

Professor A. Acosta
California Institute of Technology
Pasadena, California 91109

Dr. Irving C. Statler, Head
Applied Mechanics Department
Cornell Aeronautical Lab. Inc.
P. O. Box 235
Buffalo, N. Y. 14204

Professor S. Siestrunck
Bureau D'Analyse de Recherches
Appliquees
6 Rice Louis Pasteur
92 Boulogne, France

The Principel
College of Engineering
Guindy, Madras-25
India

Ir. W. Spuyman
Netherlands Ship Research Centre
Mekelweg 2
Delft, The Netherlands

Prof. Ir. J. Gerritsma
Head Shipbuilding Lab., Tech. Univ.
Mekelweg 2
Delft, The Netherlands

Professor Carl Prohaska
Hydro-og Aerodynamisk Laboratorium
Lyngby, Denmark

Mr. Alfonso Alcedan L., Director
Laboratorio Nacional de Hydraulics
Antiguo Cameno A. Ancon
Casilla Jostal 682
Lima, Peru

Professor J. K. Lunde
Skipmodelltanken
Trondheim, Norway

Dr. K. Taniguchi
Mitsublishi Shipbuilding & Eng. Co.
Nagasaki, Japan

Research Committee in Information
The American Society of Mechanical Engs.
345 East 47th Street
New York, New York 10017 (2)

Socitety of Naval Architects and
Marine Engineers
74 Trinity Place
New York, New York 10006

Convair Division of General Dynamics
P.O. Box 12009
Attn: Library (128-00)
San Diego, Calif. 92112

Editor
Applied Mechanics Review
Southwest Research Institute
8500 Culebra Road
San Antonio, Texas 78206

The Western Company
Research Division
2201 North Waterview Parkway
Richardson, Texas 75080

Chrysler Corporation
MGR. Advance Projects Organ.
P.O. Box 1827
Detroit, Michigan 48231

Director
Hudson Laboratories
Dobbs Ferry, New York 10522

Ocean Systems
North American Aviation, Inc.
12214 Lakewood Blvd.
Downey, California 90241

Mr. Eugene F. Baird
Chief of Dynamic Analysis
Grumman Aircraft Eng. Corp.
Bethpage, Long Island, N.Y. 11714

Dr. B. Sternlicht
Mechanical Technology Incorporated
968 Albany-Shaker Road
Latham, New York 12110

Mr. P. Eisenberg, President
Hydronautics, Inc.
Pindell School Rd.
Howard Conuty
Laurel, Md. 20810

Dr. Jack Kotik
TRG. Incorporated
Route 110
Melville, New York 11746

Mr. R.E. MacPherson
Oak Ridge National Laboratory
P.O. Box Y
Oak Ridge, Tennessee 37831

Dr. F. R. Hama
Jet Propulsion Laboratory
4800 Oak Grove Drive
Pasadena, California 91103

Dr. Ralph A. Burton
Southwest Research Institute
San Antonio, Texas 78212

Dr. H. N. Abramson
Southwest Research Institute
8500 Culebra Road
San Antonio, Texas 78228

Mr. Warren Bloomfield
Manager, Systems Engineering
Lycoming Division Avco Corporation
Stratford, Connecticut 06497

Dr. F. W. Boggs
U. S. Rubber Company
Research Center
Wayne, New Jersey 07470

Mr. A. Silverleaf
National Physical Laboratory
Teddington, Middlesex, England

Mr. R. W. Kermeen
Lockheed Missiles & Space Company
Department 57101 Bldg. 150
Sunnyvale, California 94086

Otto Decker, Manager
Friction & Lubrication Lab.
Franklin Institute
20th & Parkway
Philadelphia, Penna 19103

Dr. Paul Kaplan
Oceanics, Inc.
Plainview, Long Island, N. Y. 11803

Mr. Ross Hatte, Chief
Marine Performance Staff
The Boeing Co., Aero-Space Division
P. O. Box 3707
Seattle, Washington 98124

Dr. A. Powell
Code 900
N. S. R. D.
Washington, D. C. 20007

Mr. H. Stern
Manager, Fluids Branch
General Electric Company
P.O. Box 8
Schenectady, New York 12301

Mr. Schuyler Kleinhans
Vice President - Engineering
Douglas Aircraft Company, Inc.
Santa Monica, California 90406

R. H. Oversmith, Mgr. Ocean Engrg
General Dynamics Corp/E. B. Div.
Marine Technology Center
P.O. Box 911
San Diego, Calif. 92112

W. B. Barkley
General Dynamics Corp.
Electric Boat Division
Marine Tech. Center
P.O. Box 911
San Diego, California 92112

Commanding Officer
Attn: Tech. Lib. (Bldg) 313
Aberdeen Proving Ground, Md. 21005

Commander
Portsmouth Naval Shipyard
Portsmouth, New Hampshire 03801

Unclassified

Security Classification

DOCUMENT CONTROL DATA - R&D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY (Corporate author) California Institute of Technology Division of Engineering and Applied Science	2a. REPORT SECURITY CLASSIFICATION Unclassified 2b. GROUP Not applicable

3. REPORT TITLE

ULTRASONIC CAVITATION IN LIQUID HELIUM

4. DESCRIPTIVE NOTES (Type of report and inclusive dates)

Technical Report

5. AUTHOR(S) (Last name, first name, initial)

Hsieh, Din-Yu

6. REPORT DATE	7a. TOTAL NO. OF PAGES	7b. NO. OF REFS
March 1968	12	14

8a. CONTRACT OR GRANT NO. N00014-67-0094-0009 b. PROJECT NO. c. d.	9a. ORIGINATOR'S REPORT NUMBER(S) Report No. 85-44 9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report)

10. AVAILABILITY/LIMITATION NOTICES

Qualified requesters may obtain copies of this report from DDC.

11. SUPPLEMENTARY NOTES	12. SPONSORING MILITARY ACTIVITY
	Office of Naval Research

13. ABSTRACT

Based on the new interpretation that rotons behave like tiny quantized vortex rings, a theory is constructed to give a complete picture of ultrasonic cavitation in liquid helium. The problem of nuclei of cavitation is approached from a new direction. Questions like the λ-peak of the audible threshold, the distinction among audible, incipient visible and desinent visible cavitation thresholds in He II, the lack of such distinction in He I, the reduction of audible threshold by rotation in He II and the absence of such reduction in He I, are satisfactorily explained. The relevance of the present theory to cavitation in ordinary liquids is briefly discussed.

DD FORM 1 JAN 64 1473

Unclassified

Security Classification

Unclassified

Security Classification

14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Superfluid liquid helium						
Ultrasonic cavitation						

INSTRUCTIONS

1. ORIGINATING ACTIVITY: Enter the name and address of the contractor, subcontractor, grantee, Department of Defense activity or other organization *(corporate author)* issuing the report.

2*a*. REPORT SECURITY CLASSIFICATION: Enter the overall security classification of the report. Indicate whether "Restricted Data" is included. Marking is to be in accordance with appropriate security regulations.

2*b*. GROUP: Automatic downgrading is specified in DoD Directive 5200.10 and Armed Forces Industrial Manual. Enter the group number. Also, when applicable, show that optional markings have been used for Group 3 and Group 4 as authorized.

3. REPORT TITLE: Enter the complete report title in all capital letters. Titles in all cases should be unclassified. If a meaningful title cannot be selected without classification, show title classification in all capitals in parenthesis immediately following the title.

4. DESCRIPTIVE NOTES: If appropriate, enter the type of report, e.g., interim, progress, summary, annual, or final. Give the inclusive dates when a specific reporting period is covered.

5. AUTHOR(S): Enter the name(s) of author(s) as shown on or in the report. Enter last name, first name, middle initial. If military, show rank and branch of service. The name of the principal author is an absolute minimum requirement.

6. REPORT DATE: Enter the date of the report as day, month, year; or month, year. If more than one date appears on the report, use date of publication.

7*a*. TOTAL NUMBER OF PAGES: The total page count should follow normal pagination procedures, i.e., enter the number of pages containing information.

7*b*. NUMBER OF REFERENCES: Enter the total number of references cited in the report.

8*a*. CONTRACT OR GRANT NUMBER: If appropriate, enter the applicable number of the contract or grant under which the report was written.

8*b*, 8*c*, & 8*d*. PROJECT NUMBER: Enter the appropriate military department identification, such as project number, subproject number, system numbers, task number, etc.

9*a*. ORIGINATOR'S REPORT NUMBER(S): Enter the official report number by which the document will be identified and controlled by the originating activity. This number must be unique to this report.

9*b*. OTHER REPORT NUMBER(S): If the report has been assigned any other report numbers *(either by the originator or by the sponsor)*, also enter this number(s).

10. AVAILABILITY/LIMITATION NOTICES: Enter any limitations on further dissemination of the report, other than those imposed by security classification, using standard statements such as:

(1) "Qualified requesters may obtain copies of this report from DDC."

(2) "Foreign announcement and dissemination of this report by DDC is not authorized."

(3) "U. S. Government agencies may obtain copies of this report directly from DDC. Other qualified DDC users shall request through ________________."

(4) "U. S. military agencies may obtain copies of this report directly from DDC. Other qualified users shall request through ________________."

(5) "All distribution of this report is controlled. Qualified DDC users shall request through ________________."

If the report has been furnished to the Office of Technical Services, Department of Commerce, for sale to the public, indicate this fact and enter the price, if known.

11. SUPPLEMENTARY NOTES: Use for additional explanatory notes.

12. SPONSORING MILITARY ACTIVITY: Enter the name of the departmental project office or laboratory sponsoring *(paying for)* the research and development. Include address.

13. ABSTRACT: Enter an abstract giving a brief and factual summary of the document indicative of the report, even though it may also appear elsewhere in the body of the technical report. If additional space is required, a continuation sheet shall be attached.

It is highly desirable that the abstract of classified reports be unclassified. Each paragraph of the abstract shall end with an indication of the military security classification of the information in the paragraph, represented as *(TS)*, *(S)*, *(C)*, or *(U)*.

There is no limitation on the length of the abstract. However, the suggested length is from 150 to 225 words.

14. KEY WORDS: Key words are technically meaningful terms or short phrases that characterize a report and may be used as index entries for cataloging the report. Key words must be selected so that no security classification is required. Identifiers, such as equipment model designation, trade name, military project code name, geographic location, may be used as key words but will be followed by an indication of technical context. The assignment of links, rules, and weights is optional.